67/5

Instruction Manual

MODEL V-4700A

RUBIDIUM VAPOR FREQUENCY STANDARD

PHILCO CORPORATION
Vandenberg Air Force Base
Serial No. 14

September, 1962

Publication No.
87-000-049

TABLE OF CONTENTS

TABLE OF CONTENTS (Con't)

TABLE OF CONTENTS (Con't)

LIST OF FIGURES

LIST OF FIGURES (Con't)

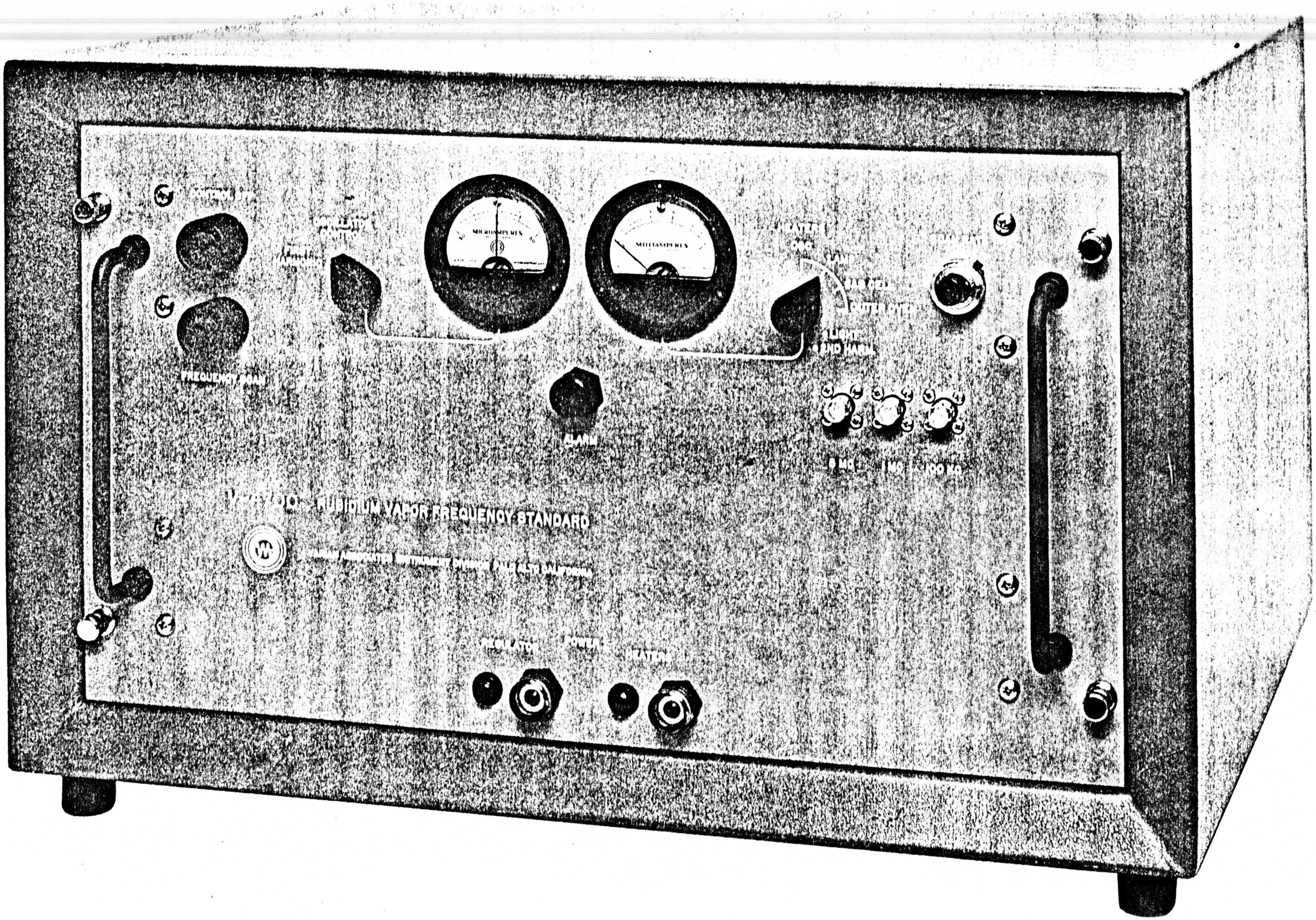

FIGURE 1-1. FRONT PANEL, V-4700A RUBIDIUM VAPOR FREQUENCY STANDARD

MODEL V-4700A RUBIDIUM VAPOR FREQUENCY STANDARD

INSTRUCTION MANUAL

1.0 INTRODUCTION

1.1 PURPOSE

The Varian Model V-4700A Rubidium Vapor Frequency Standard is an instrument designed to provide highly stable frequency outputs at 5 mc, 1 mc, and 100 kc.

1.2 GENERAL DESCRIPTION

This instrument utilizes the principles of optical pumping and transmission monitoring. By means of these techniques, the 5 mc crystal oscillator is stabilized against the invariant field independent hyperfine transition of rubidium 87. The instrument is designed for continuous operation.

Figure 1-1 shows a front view of the V-4700A Rubidium Vapor Frequency Standard. Front panel controls and metering are provided for locking the oscillator to the atomic transition and monitoring the operation of the instrument. Rear control and monitoring points are provided for initial adjustment of the instrument.

1.3 GENERAL SPECIFICATIONS

Output Frequencies	5 mc, 1 mc, and 100 kc simultaneously. Additional frequencies are available upon special request.
Output Level	5 mc and 1 mc: 1v rms into 50 ohms. 100 kc: 1v rms into 50 ohms, or minimum 3v into approximately 15,000 ohms, selected by internal switch.
Long Term Stability	5×10^{-11} in any 1-year period (Standard Deviation).

1.3 GENERAL SPECIFICATIONS (Con't)

Short Term Stability	1×10^{-11} for a one-second averaging time (Standard Deviation)
Spectral Purity	Less than 2 cps bandwidth at 24 kmc when derived from 5 mc output.
Environmental Stability	Above long- and short-term stability specifications are maintained over the following conditions: Humidity: 0 to 95% Temperature: 15^{o} to 35^{o} C. Input Voltage: ± 15% of nominal Load: Open to short circuit
Accuracy and Frequency	Instrument is calibrated to any customer-specified time scale within 4×10^{-8} of A.1, to an accuracy of $\pm 1 \times 10^{-10}$ relative to the U. S. Frequency Standard.
Fine Tuning Precision	Magnetic field tuning allows adjustment of frequency over a range of $+5 \times 10^{-9}$ to a setting precision of 1×10^{-11}.
Stabilization Time	Instrument accuracy is $\pm 1 \times 10^{-10}$ after a two-hour warmup. Turn-off/turn-on repeatability $\pm 2 \times 10^{-11}$ after 12-hour warmup.
Crystal Oscillator Locking System	Crystal oscillator frequency is locked to the RB^{87} hyperfine frequency by an entirely electronic integrating servo having a d-c gain of approximately 10^{8} and a unity gain point of 70 cps.
Alarm Indicator	Front panel alarm light indicates visually that the output frequency is locked to the hyperfine transition frequency. Rear terminals connected to relay contacts provide for remote alarm systems.
Input Requirements	28v dc nominal, at 2a.
Packaging	The frequency standard is housed in a cabinet accommodating a 19-inch panel. Cabinet dimensions are 21-7/16 inches wide x 12-7/8 inches deep (2.9 cu. ft.). Total weight is approximately 95 pounds.

1.4 V-4760 STANDBY POWER SUPPLY

1.4.1 Purpose

The Varian V-4760 Standby Power Supply, shown in Figure 1-2, is specifically intended for use with the Varian V-4700A Rubidium Vapor Frequency Standard. It is designed to operate with standby batteries floating across the output in order to provide continuous d-c power in the event of line failure. A 20 cell nickel cadmium battery is recommended. Cell size should be chosen to provide 2.5 amps for the required standby period. The battery is to be provided by the customer.

1.4.2 General Specifications

Output Voltage	28 volts dc, during normal operation. 31 volts dc, during charging cycle.
Output Current	5 amps regulated; short circuit current passively limited to 10 amps.
Input Power	115 volts, 60 cps; 50 cps model available upon special request. Approximately 500 watts maximum input power.
Front Panel Metering	D-c output voltage and battery charge/discharge current.
Front Panel Controls	Input power circuitbreaker with 5-amp capacity. Battery charge/discharge circuitbreaker with 10-amp capacity. Battery over-voltage charging timer.
Packaging	Power supply is normally housed in a cabinet but can be removed for 19-inch rack mounting. Cabinet dimensions are 21-7/16 inches wide x 7-3/4 inches high x 18 inches deep (1.8 cu. ft.). Total weight is approximately 53 pounds. Rack mounting height is 5-1/4".

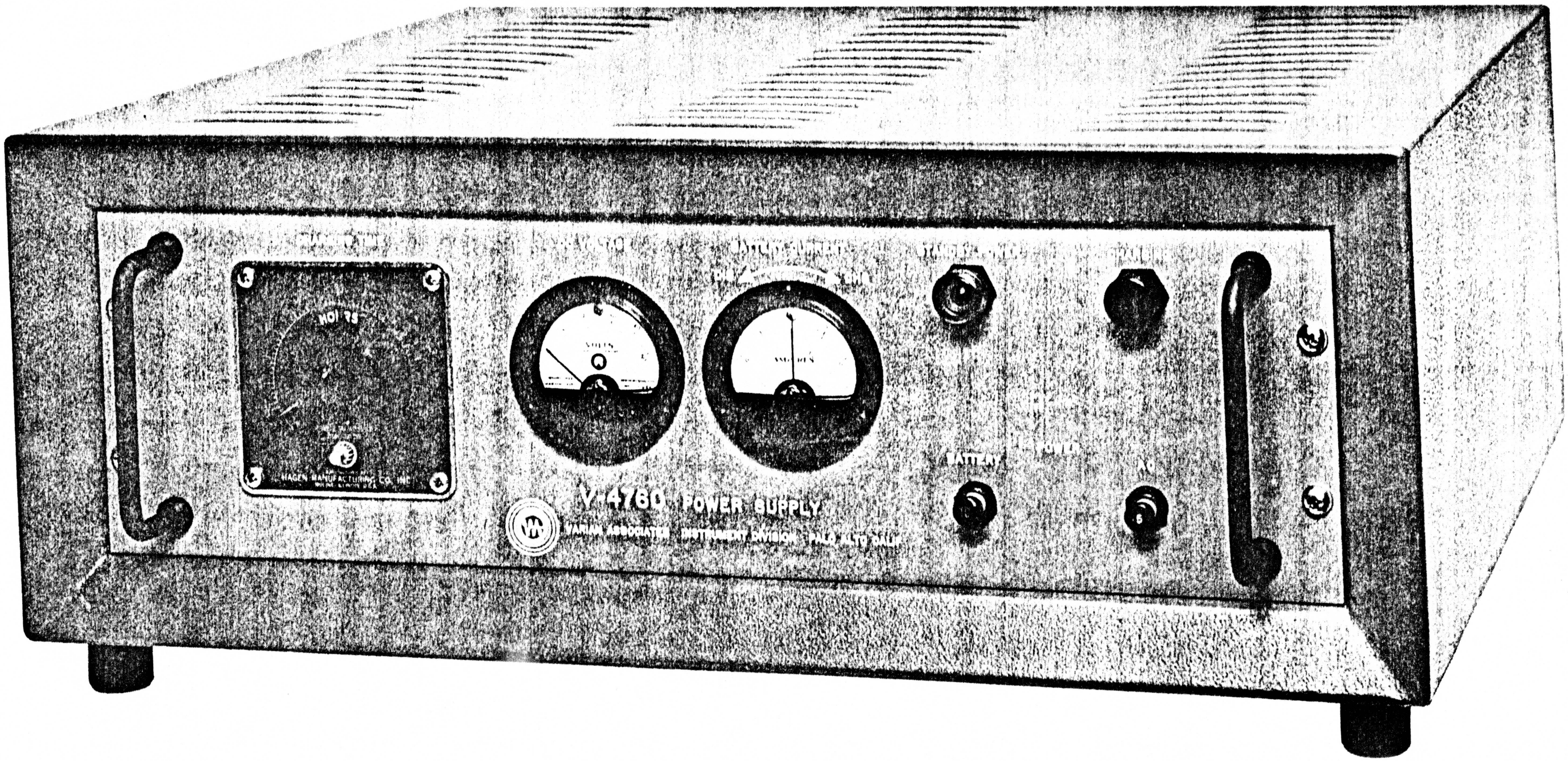

FIGURE 1-2. FRONT PANEL, V-4760 POWER SUPPLY

2.0 THEORY OF OPERATION

2.1 PRINCIPLES OF OPTICAL PUMPING AND TRANSMISSION MONITORING

The instrument uses optical pumping and transmission monitoring to detect the atomic hyperfine transition of Rb^{87}. This hyperfine splitting arises from the interaction between the electron spin, $S = 1/2$, and the Rb^{87} nuclear spin, $I = 3/2$, and is in free space at a frequency of 6,834,682,614 cps.

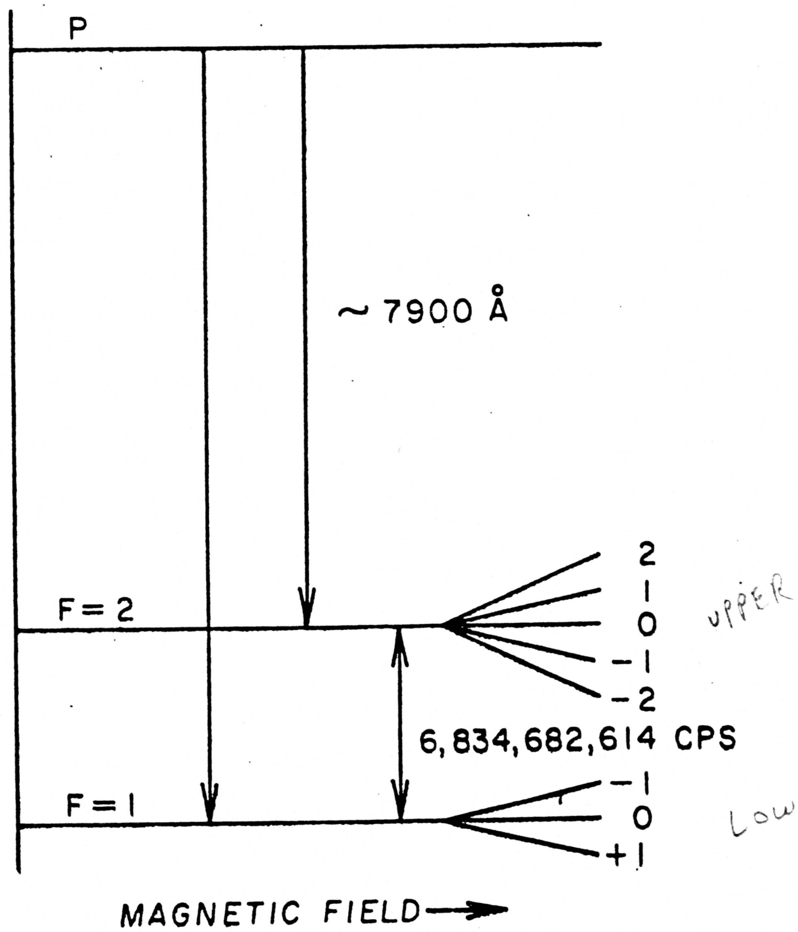

FIGURE 2-1

The first excited states of the Rb^{87} atom are P 1/2 and P 3/2, at wave lengths 7947 Å and 7800 Å, respectively, above the ground state.

Figure 2-1 shows a simplified Rb^{87} energy level diagram, in which only one of the P-states is considered and P-state hyperfine spliting is neglected. The upper hyperfine level, characterized by $F = 2$, is split under the application of a magnetic field into the five levels m_F 2, 1, 0, -1, -2; the lower hyperfine level, characterized by $F = 1$, is similarly split into the three levels m_F -1, 0, 1. The transition from the $F = 2$, $m_F = 0$ level to the $F = 1$, $m_F = 0$ level is virtually independent of magnetic field and is the one used to stabilize the oscillator frequency. This is called the field independent or zero-zero transition.

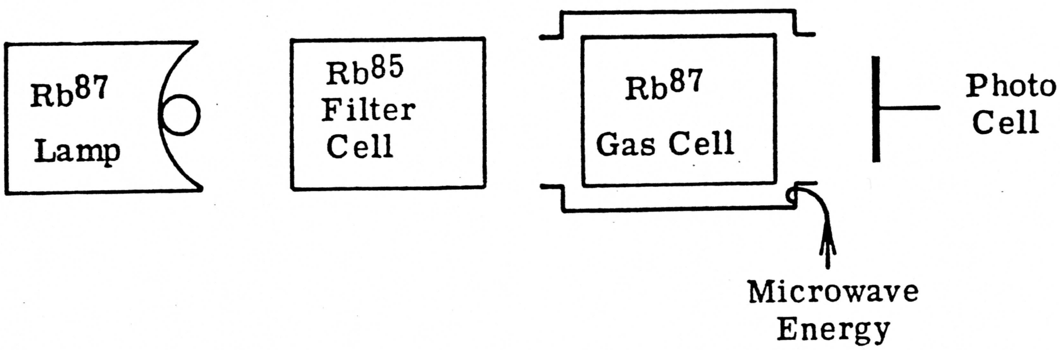

FIGURE 2-2

Figure 2-2 gives a block diagram of the optical system. In terms of Figure 2-1, the Rb^{87} lamp emits spectral radiation of approximately 7900 Å wavelength from the P-state to each of the ground state hyperfine levels, $F = 1$ and $F = 2$. If the Rb^{87} atoms in the gas cell are irradiated by Rb^{87} light which has the lower energy hyperfine component removed, optical transitions will occur only between the lower hyperfine level ($F = 1$) and the excited P-state. Once in the P-state atoms can decay with equal probability to any one of the eight ground state sub-levels. Those which decay to one of the lower energy hyperfine sub-levels

will again be pumped to the excited state; those which decay to the upper hyperfine sub-levels will be unaffected by the light since spectral components which can cause transition from this level have been filtered out. The result is a transfer of population from the optically opaque lower hyperfine level to the optically transparent upper hyperfine level.

The lower energy hyperfine component is removed from the light by a rubidium 85($I = 5/2$) filter cell between the lamp and gas cell. This cell contains Rb^{85} vapor in a carrier gas of a few cm neon, argon, or krypton. The splitting between hyperfine components of the Rb^{85} absorption lines is about half that of Rb^{87}. In addition, because of the different nuclear spin the lower energy Rb^{85} hyperfine component lies considerably closer to the lower energy Rb^{87} hyperfine component than does the higher energy Rb^{85} component to the higher energy Rb^{87} component. The net result is that with carrier gas pressure broadening the lower energy Rb^{85} hyperfine absorption component overlaps the corresponding Rb^{87} emission line and selectively filters it from the light incident on the gas cell. These effects are illustrated in Figure 2-3

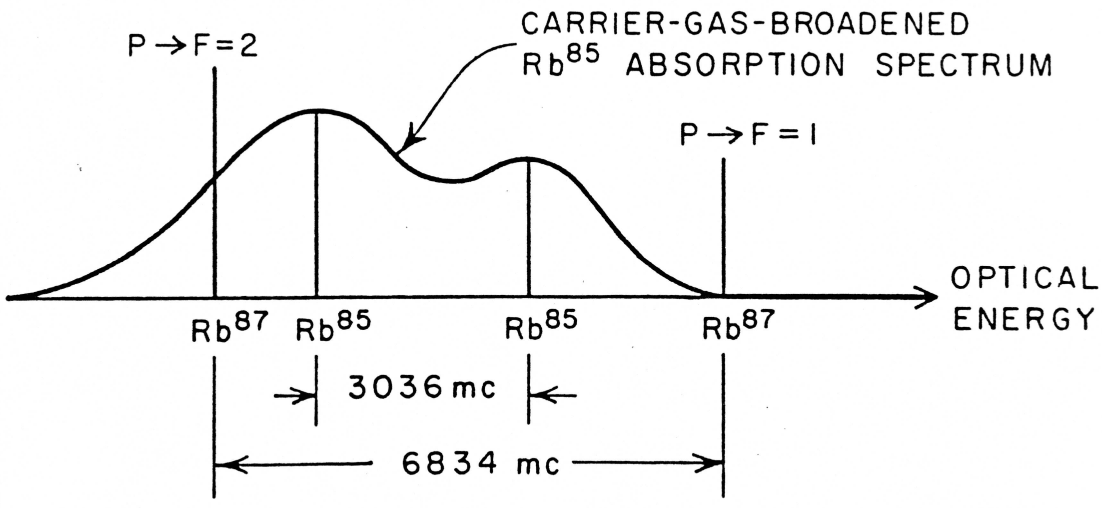

FIGURE 2-3

A microwave magnetic field at the hyperfine frequency will induce transitions between the optically transparent F 2, m_F 0 level, and the optically aborbing F 1, m_F 0 level, and a decrease in light intensity will be noted on the photocell monitoring the transmitted light beam. The signal from the photocell is used to stabilize the oscillator generating the microwave frequency.

To obtain narrow resonance lines, it is necessary that the frequency of disorienting collisions of the rubidium atoms with the walls of the gas cell be reduced to a low level. This is done by use of a buffer gas of 55% neon - 45% argon at approximately 8 mm pressure. In addition to giving narrow lines the buffer gas causes a shift in hyperfine frequency from its free space value of 6,834,682,614 cps. Advantage is made of this shift to simplify the problem of synthesizing the hyperfine frequency from the 5 mc oscillator. The hyperfine frequency is adjusted to be 6834-13/19 6834.684211 mc on whatever time scale is selected with the instrument; time scales may be changed by a simple change of cavity and gas cell.

While the zero-zero hyperfine frequency has no first order magnetic field dependence, a second order effect given by: $\frac{\delta f}{f} = -0.84 \times 10^{-7} H^2$ (H=gauss) exists. Magnetic field tuning may be used to adjust the frequency upward from zero field and may be used to bring standards into precise phase and frequency synchronization in synchronized time networks. Additionally magnetic field tuning may be used to cover all customarily used time scales with one gas cell. By filling the gas cell -170×10^{-10} relative to A.1, UT_2 for some years in the future, A.1, and the time scale -76×10^{-10} relative to A.1, used with commercial cesium beam frequency standards can all be reached within a tuning range of 2×10^{-8}. To maintain stability against changes in environmental magnetic fields, a triple mu-metal magnetic shield with a shielding factor in excess of 1000 is used; with this shield, a change ambient field of one gauss in the worst direction will give a frequency change of less than 1×10^{-10} at the maximum offset of 2×10^{-8}.

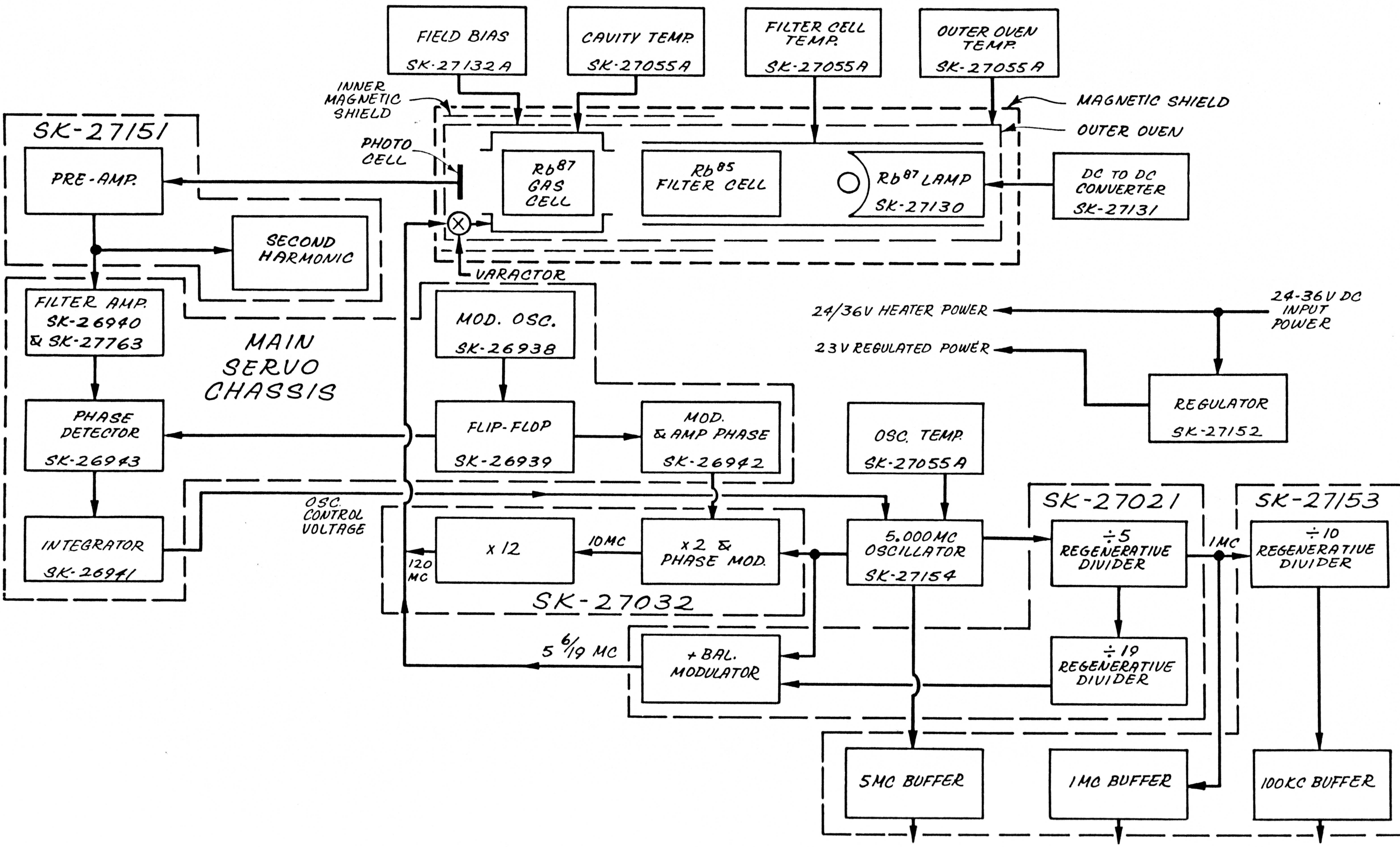

FIGURE 2-4 FREQUENCY STANDARD BLOCK DIAGRAM

2.2 PRINCIPLES OF V-4700A RUBIDIUM VAPOR FREQUENCY STANDARD OPERATION

Figure 2-4 shows a block diagram of V-4700A Rubidium Vapor Frequency Standard. The frequency standard consists of five major subsystems, the RF system, optical system, servo system, regulator, and temperature controllers.

2.2.1 RF System

2.2.1.1 5 mc Oscillator

The oscillator uses a 5 mc fundamental crystal in a circuit designed to give high short-term stability. The MECHANICAL TUNING control on the rear of the instrument provides an oscillator tuning adjustment of approximately 2×10^{-6}. Frequency control is accomplished by application of the oscillator control voltage from the servo system to a Varicap (voltage variable capacitor) in the oscillator circuit. The crystal and oscillator components are controlled in temperature at the crystal turn-over point.

2.2.1.2 Multiplier

The 5 mc output of the oscillator is doubled to 10 mc, phase modulated at a 107 cps rate, and then multiplied to 120 mc. MODULATION AMPLITUDE and MODULATION PHASE adjustments are made by rear servo controls.

2.2.1.3 Synthesizer

Regenerative division is used to divide 5 mc to 1 mc. As part of this divider, 6 mc is also produced. By regenerative division, 6 mc

is divided by 19 to give 6/19 mc. This frequency is then added to 5 mc in a single sideband balanced modulator to give 5-6/19 mc. All regenerative dividers in this instrument are made to start automatically through use of starting oscillators; this oscillator is gated off when the divider operates with an input signal. No output appears unless there is an input signal.

2.2.1.4 Buffer

Regenerative division is used to give 100 kc from the 1 mc input from the synthesizer. In addition, this unit contains the doubler to 10 mc and the buffer amplifiers for the 10 mc, 5 mc, 1 mc, and 100 kc outputs of the instrument.

2.2.1.5 Varactor Multiplier

5-6/19 mc from the synthesizer is brought into the multiplier and put on the same coaxial line with 120 mc. This line then goes to the MA460E varactor diode located in a mount on the end of the microwave cavity. In the diode 120 mc is multiplied by 57 to give a microwave frequency of 6840 mc. The first order lower sideband created by the 5-6/19 mc modulation of the diode then gives a frequency of 6834-13/19 mc; as mentioned previously, this is the frequency to which the gas cell is filled and sealed.

2.2.2 Optical System

The optical system is contained inside a mu-metal shield to shield it from environmental magnetic fields.

2.2.2.1 Lamp and Filter Cell

This assembly contains the lamp and Rb^{85} filter cell in one thermally controlled package. The lamp is driven in an electrodeless RF discharge by a two-tube lamp oscillator operating at a frequency

somewhat in excess of 100 mc. The lamp should operate for over 10,000 hours. A neutral density filter is placed on the end of the lamp-filter cell package to reduce light intensity in the gas cell to the desired value.

2.2.2.2 Cavity, Gas Cell, and Photocell

The cavity, gas cell, and photocell form one thermally controlled unit. The cavity has been factory tuned to the hyperfine frequency. The incident light intensity is adjusted to give an operating line width of approximately 160 cps.

2.2.2.3 Outer Oven, Field Bias, and Inner Magnetic Shield

The thermally controlled lamp-filter cell and cavity gas cell packages are contained in a thermally controlled outer oven, which gives a high degree of thermal shielding to these components. Magnetic field tuning, adjustable through the FIELD BIAS control on the rear of the instrument, provides fine tuning of the unit. An inner mu-metal magnetic shield provides additional shielding to the gas cell.

2.2.3 Servo System

2.2.3.1 Preamplifier

The output of the photo cell goes to a high speed chopper preamplifier designed to minimize excess noise from the silicon solar cell and input transistor. Figure 2-5 shows a resonance signal as seen at the rear scope terminals.

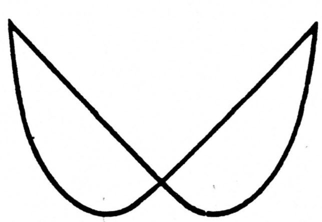

FIGURE 2-5

2.2.3.2 Second Harmonic Circuitry

At resonance the signal from the photocell contains only even harmonics, predominately second harmonic. The second harmonic content of the signal from the photocell is used as an indication of signal strength and that the system is locked. The output of preamplifier is passed through a second harmonic filter and rectified. This rectified 2nd Harmonic output is metered on the front panel; in addition a relay is activated by the second harmonic level. If it drops below some preset level, the ALARM light goes on on the front panel and EXTERNAL ALARM contacts connected to a plug on the rear of the instrument are tripped.

2.2.2.3 Filter Amplifier

A sharp notch filter removes the second harmonic in the signal channel. The signal is further amplified and may be controlled in gain by the AMPLIFIER GAIN control on the rear of the instrument.

2.2.3.4 Modulation Oscillator and Trigger

The basic modulation oscillator operates at 214 cps, which is twice the modulation frequency. A sharp trigger spike is then derived from the output of this oscillator.

2.2.3.5 Flip-Flop

The flip-flop is triggered by these spikes and divides the modulation oscillator frequency to 107 cps. The timing symmetry between the two states of the flip-flop is better than 1×10^{-5}. This precisely timed output is used as the reference to the phase detector.

2.2.3.6 Modulation Amplitude and Phase

The output of the flip-flop is filtered to a sine wave and then controlled by the rear MODULATION AMPLITUDE and MODULATION

PHASE controls before being applied to the phase modulator in the RF multiplying chain. Because of the precise manner in which it is derived the modulating waveform has an even harmonic content smaller than 1×10^{-4}.

2.2.3.7 Phase Detector

A transistor phase detector with low offset error is used to convert error information carried at the modulation frequency to error information about dc. The output of the phase detector may be metered on the FIRST HARMONIC position on the front panel. The phase of the signal to the phase detector may be inverted by the rear PHASE INVERSION switch.

2.2.3.8 Operational Amplifier

The operational amplifier is a very high gain chopper-stabilized d-c amplifier which is used with a feedback capacitor to provide an all-electronic integrator. Other circuitry associated with the operational amplifier is used to shape the gain-frequency characteristics of the frequency control servo loop at frequencies above 1/5 cps. In normal operation the loop gain of the system is unity somewhere between 40 and 60 cps. From here to 1/5 cps, the loop gain is brought up at 12 db/octave to give a loop gain of over 400 at 1 cps. Below 1/5 cps the loop has integral control with loop gain increasing 6 db/octave with decreasing frequency. The total d-c loop gain is in excess of 10^8, which is so large as to be meaningless. The important criterion is drift stability of the phase detector and operation amplifier; typical variations in these should cause frequency errors no greater than 2×10^{-12}. The gain of the operational amplifier feedback loop may be controlled by the INTEGRATOR GAIN control on the rear of the instrument.

2.2.4 Regulator

The power requirements of the V-4700A are 2.5 amps at 24-36 v dc. All circuits except the heaters operate from the output of a 23 v regulator. This isolates these circuits from supply voltage fluctuations as batteries are discharged and charged.

2.2.5 Temperature Controller

The crystal oscillator, lamp-filter cell package, cavity-gas cell, and outer oven all have proportional temperature control. The controllers use a sensing thermistor in a bridge circuit driven by a separate oscillator, an amplifier, and a phase-sensitive detector whose output actuates a power transistor controlling heater current.

2.2.6 V-4760 Standby Power Supply

The power requirements for the V-4760 Standby Power Supply are 117 vac ±10% 60 cycles, at approximately 120 watts. The basic d-c power is supplied by a Sola constant voltage transformer-rectifier combination at 28 vdc or 31 vdc. The unit is designed to be operated with nickel-cadmium or lead-acid standby batteries. The basic power source is passively self-limiting in current at approximately 10 amps and thus has the required characteristics as a battery charger. The normal output voltage from this portion of the power supply is 28 v; the voltage may be raised to 31 v by turning on the CHARGING TIME timer. This overvoltage, which is turned off in the period of time set on the CHARGING TIMER, is used to fully recharge nickel-cadmium batteries. If lead-acid batteries are used, the timer need not be used. If batteries are used they remain floating across the power supply and without switchover will deliver power if 60 cycle power is turned off.